The Dynamics and Physics of Multiple Strait Systems

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LONG-TERM GOALS

To determine how island groups interact, so enabling us to evaluate how best to 'parameterize' these groups in 3-D numerical ocean models used in forecasting, which cannot necessarily resolve all of the islands and interconnecting straits. The theories and models are being developed in a general framework, so that they have application to arbitrary multiple-strait systems.

OBJECTIVES

1. To adapt and extend, as necessary, the analytical techniques developed to investigate flow through and within the Indonesian archipelago to the Caribbean.

2. To derive estimates of transport through Makassar Strait from the ARLINDO current meter data.

APPROACH

1. Caribbean Circulation: It has long been the conclusion that it is coincidence that the transport through Florida Strait is the same as the value of the Sverdrup streamfunction there. Observations of South Atlantic water masses within the Strait (Schmitz and Richardson, 1991), as well as discrepancies on the northward heat transport (Wunsch and Roemmich, 1985), dictate that the northward flow cannot be the return flow of a subtropical, anticyclonic, Sverdrup gyre. However, recent high-resolution, global simulations (e.g. Maltrud et al., 1998) show remarkable agreement between the barotropic streamfunction field and the equivalent wind-driven circulation calculated assuming Sverdrup balance in the ocean interior. The dichotomy is reminiscent of that for the Indonesian seas, where a Sverdrup model gives a predominantly South Pacific fed Indonesian throughflow, whereas observations suggest that it should be fed predominantly from the North Pacific. The resolution is similar in that it needs to be recognized that the properties of the western boundary layer are crucial to determining water mass composition. For the Indonesian throughflow problem, nonlinearity within the western boundary layer had to be invoked (Wajsowicz, 1999). For the Caribbean, a meridional-overturning thermohaline circulation confined to the western boundary layer over the latitudes of the Caribbean, and frictional effects within straits, need to be invoked.

2. Makassar Strait Transports: The ARLINDO current meter data from two moorings in Labani Channel, Makassar Strait about 18km apart form an important data set even though their 20-month and 16-month records contain data for the upper 250m for only 3 months of the shorter record. It is unlikely that a more complete data set, in terms of depth-range or temporal coverage, will be available for at least another 5 years, maybe even 10 years. The moorings (jointly funded by ONR and NSF) were sited under the assumption that most of the transport associated with the Indonesian throughflow passes through the Channel. Given the importance of the Indonesian throughflow in climate-related issues, and circulation within the Indonesian seas and Indian Ocean, this data set needs to be exploited as best it can. Makassar Strait is about 2000m deep along its length and about 200km wide (measured by the 1000m isobath). The width of the Strait narrows to about 50km at Labani Channel, about two-thirds of the way along its length. The reduction in width is not particularly abrupt, and so the horizontal-scale of the motion is expected to be much larger than the vertical-scale. Hence, the energy in the low-frequency (seasonal timescales and longer) motion should be distributed in the low-order baroclinic normal modes given by

$$(d/dz)\{N^{-2}(dp/dz)\} = -c_e^2 p, \ (dp/dz)=0 \text{ at } z= -H,0$$

where N is the background buoyancy frequency. The modes form a complete, orthonormal set, and so irrespective of whether hydraulic effects are sufficient to make the equations of motion inseparable, the modes can describe the velocity profiles exactly.

WORK COMPLETED

1. Caribbean Circulation: First, the multiple-island rule, Wajsowicz (1993), was extended to an arbitrary length chain of n overlapping islands. Expressions for the transports in the straits between islands were derived. The methodology was extended to include friction, assumed proportional to the strait transport. Asymptotic solutions in the limit of small and large friction coefficient were determined. A suitable geometry for applying the multiple-island rule to the Caribbean was determined from the ETOPO5 bathymetry data set and published navigational charts. The island boundaries were coded into the computer and the layers of overlapping island determined. The wind-stress curl was calculated from Hellerman and Rosenstein (1983) climatology. Then, the circulation on each island was calculated from the multiple-island rule, Wajsowicz (1993). The basinwide transport streamfunction was then calculated from the Sverdrup balance, inserting the previously obtained results for the island circulations. Relative vorticity was assumed destroyed at the latitude of creation in the western boundary layer, so that the streamfunction increased/decreased monotonically to the neighboring land value. The interaction between the island circulations as the friction coefficients varied was calculated. The model was extended to three layers to permit the inclusion of a simple thermohaline circulation. Assuming there is no downwelling/upwelling between the layers over the latitudes of the Caribbean, then the equations of motion for the upper layer are as before, but the boundary condition on the American continent is now that the streamfunction equals the magnitude of the thermohaline circulation, instead of the value on the African continent. The upper limb of the thermohaline circulation effectively passes through the region as a western boundary current. The multiple-island rule calculations were repeated as before. A suitable combination of friction coefficients were identified, which yielded transports throughout the Caribbean in agreement with observations.

2. Makassar Strait Transports: The buoyancy frequency profiles for the Indonesian archipelago and Makassar Strait were calculated from temperature and salainity data from NODC's World Ocean DataBase 1998 and the ARLINDO cruises. The climatology mean profile was used to calculate a set of normal modes. As the velocity profiles in the ARLINDO data set are severely truncated, the normal modes are fitted one at a time using a least-squares criterion with the next mode fitted to the residual, and so on. All permutations of fit order for the first three baroclinic modes are considered to give a spread for the resulting coefficients, which may be regarded as a measure of the error associated with the profile recovery. To determine whether the coefficients obtained were reasonable, and whether the Fourier value (the value obtained if the velocity data had extended over the total depth) lie within the range obtained, results from a GCM were examined with tests made on truncating the profiles.

The data set extended for only 20 months and another issue is whether information on climatological mean and seasonal values could be determined from such a short data set. Twenty-month samples from a 9-year time series from a GCM were examined to test the error associated with fitting mean, biannual, annual and semi-annual harmonics to the time series.

RESULTS

Caribbean Circulation: The multiple-island rule proved to be a very powerful tool for investigating the Caribbean circulation, as it identifies in closed analytical form the wind stress bands, which determine a particular strait transport. For example, the mean transport through Windward Passage depends on the wind stress integrated along island-rule paths for the Great Bahama Bank and Cuba, and only very weakly on wind stresses outside these latitudes. It also enables the features of the wind stress field in different wind stress climatologies, which cause strait transports to differ in an operational GCM, say, to be readily identified, c.f. Townsend et al.'s (2000) study of eleven wind stress climatologies. It can be used to ascertain conditions under which measurements of transport in Great Inagua Passage is a good approximation for that in Windward Passage, and when they may be misleading due to a significant western boundary current along the southeast coast of Cuba.

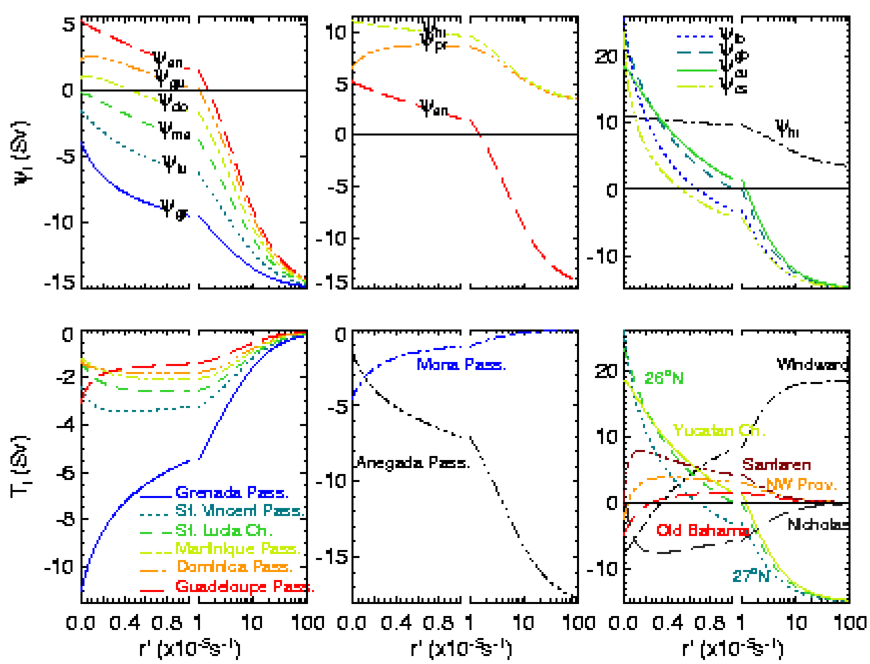

Fig. 1 The variation in island circulations (upper panel) and strait transports (lower panel) with friction coefficient r' for the eastern, central and western Caribbean from left to right. A thermohaline circulation of overturning strength 15 Sv is assumed. The Yucatan Channel, Anegada and Windward Passages are assumed dynamically wide and deep; the friction coefficients in the other passages are equal to r'.

In the absence of a thermohaline circulation, and confining frictional effects solely to western boundary layers, so that the passages were all dynamically wide and deep, yielded some weaker strait transports in the wrong direction, e.g. Santaren Channel, and some strait transports too large, e.g. Old Bahama Channel. Also, there is no western boundary current to the east of Abaco Island. Including frictional effects enabled many of these discrepancies to be resolved. Asymptotic expansions in the limit of weak and strong friction show that the wind stress dependency is extended to the latitudes spanning the whole length of the island chain and just to immediately adjacent islands to the north and south respectively.

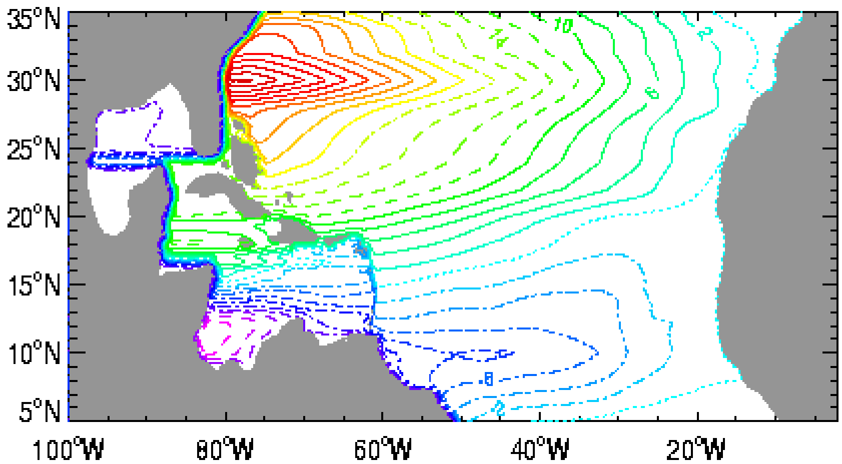

Fig. 2 The transport streamfunction in the top layer of analytical model forced by Hellerman & Rosenstein wind stress climatology, and containing the upper limb of a 15 Sv thermohaline circulation. Friction coefficients are chosen to yield strait transports similar to observed. The result is a spread of South Atlantic water masses across the southern Caribbean Sea with the remainder deflected along the outer arc of the Lesser Antilles entering via Anegada Passage. A meridional smoothing scheme is applied to smooth out the infinitesimally thin zonal jets, some of which are bi-directional, to enable the water mass pathways to be better discerned. The western boundary later scale has been exaggerated for visualization. The contour interval is 2 Sv.

Introducing frictional effects in the passages cannot resolve the major discrepancies with observations of eastward instead of westward flow in Grenada Passage, a southward instead of northward Guyana Current, and hence a Caribbean circulation and Florida Current fed wholly by water masses of North Atlantic origin. Adding a thermohaline circulation simply as a western boundary current corrects these problems, and all of the results for the wind-driven-only model carry over, but with the value of the transport streamfunction on the American continent set to the magnitude of the thermohaline overturning circulation rather than zero, the value on Africa. Realistic transports through the Windward Island passages are only obtained if the frictional resistance in these passages is an order of magnitude larger than those in the western passages. Water masses from the South Atlantic are partially deflected northward along the outer arc of the Windward Islands, and enter the Caribbean through Anegada Passage. The model suggests that for realistic friction parameters South Atlantic water masses are unlikely to be found in the more western passages, or in the western boundary current skirting the edge of the Bahama Banks.

Makassar Strait Transports: The vertical profiles are sufficiently truncated that the least-squares fit can only distinguish between the first and second baroclinic mode components to the vertical shear in about a third of the months of the record. Taking the difference between the first and second baroclinic fit realizations as a measure of the error associated with recovering the transport means that the total-depth transport estimate has an error of +/- 50%. The strictly best fit is obtained, except for a couple of months, if the second baroclinic mode is fitted first. This results in a mean velocity profile with a southward maximum at about 250m, and possibly unrealistically northward flow at the surface throughout the record. If the first baroclinic mode is fitted first, then it dominates the mean profile with a southward maximum at the surface throughout the record. Tests with a 9-year times series of transport from a GCM showed that the climatological mean and seasonal cycle could be recovered to within a couple of percent if the spectrum has distinct peaks as found in the Makassar current meter record. As it is unknown whether the first and second baroclinic mode dominance switches over during the seasonal cycle, estimates have to be given with caution. Assuming the first baroclinic mode dominates the reconstruction, then net mean transport is estimated to be about 15 Sv southwards, and the amplitudes of the annual and semi-annual harmonics in net transport are 2.4 Sv and 3.4 Sv with maximum southward transport in June and August respectively. If the second baroclinic mode dominates the reconstruction, then there is little net transport in the 250m about the data record. The estimated mean net transport is only 6 Sv, and amplitudes for the annual and semi-annual harmonics are only 0.5 Sv and 2 Sv. The two possible reconstructions suggest an interannual signal of period about 2 years with amplitude in the range 3-6 Sv and phase giving a maximum northward transport in November 1997.

IMPACT/APPLICATION

The development of sophisticated, numerical models for forecasting the ocean circulation and hydrographic state is a high priority for ONR, as is knowledge and understanding of the ocean circulation in strategically important regions such as the Indonesian archipelago, other east Asian marginal seas, and the Caribbean.

TRANSITIONS

In general terms, the P.I.'s research provides a theoretical framework in support of ONR's field programs (e.g. Gordon et al.'s ARLINDO and Sprintall et al.'s network of shallow pressure gauges in the Indonesian exit straits), and numerical primitive-equation modeling research at NRL, Mississippi (Hurlburt, Kindle and Preller) and NPGS (Semtner, Tokmakian and McClean). The methods and techniques developed are quite general, and so potentially have widespread application.

1. Caribbean Circulation Model: The results from this research will be made available shortly to members of the Intra-Americas Seas Initiative, which includes groups at RSMAS, University of Miami and AOML, as well as those listed above.

2. Makassar Transports: These results have been made available to the oceanographic community worldwide, and are being used to validate and improve GCMs everywhere.

RELATED PROJECTS

The P.I. is funded by NASA to investigate the hydrological cycle in the Indo-Pacific region, which involves running high-resolution, global numerical models. Accurate simulation of the transport of heat and fresh-water fluxes between the Pacific and Indian Oceans is crucial for these investigations. The P.I. is also funded by NOAA to investigate diabatic adjustment processes in the North Atlantic related to observed decadal-scale variability.

REFERENCES

Hellerman, S. and M. Rosenstein, 1983: Normal monthly wind stress over the world ocean with error estimates, J. Phys. Oceanogr., 13, 1093-1104.

Maltrud, M.E., R.D. Smith, A.J. Semtner, R.C. Malone, 1998: Global eddy-resolving ocean simulations driven by 1985-1995 atmospheric winds, J. Geophys. Res., 103, 30825-30854.

Schmitz, W.J. Jr., and P.L. Richardson, 1991: On sources of the Florida Current, Deep-Sea Res., 38 Supp. 1, S379-S409.

Townsend, T.L., H.E. Hurlburt, P.J. Hogan, 2000: Modeled Sverdrup flow in the North Atlantic from eleven different wind stress climatologies, Dyn. Atmos. Oceans, 32, 373-417.

Wajsowicz, R.C., 1993: The circulation of the depth-integrated flow around an island with application to the Indonesian throughflow, J. Phys. Oceanogr., 23, 1470-1484.

Wajsowicz, R.C. 1999: Variations in gyre closure at the water mass crossroads of the western equatorial Pacific Ocean, J. Phys. Oceanogr., 29, 3002-3024.

Wunsch, C. and D. Roemmich, 1985: Is the North Atlantic in Sverdrup balance?, J. Phys. Oceanogr., 15, 1876-1880.

PUBLICATIONS

Wajsowicz, R.C. 1999: Variations in gyre closure at the water mass crossroads of the western equatorial Pacific Ocean, J. Phys. Oceanogr., 29, 3002-3024.

Wajsowicz, R.C. 2000: A modified Sverdrup model of the Atlantic and Caribbean circulation, submitted to J. Phys. Oceanogr., September 2000

Wajsowicz, R.C., A.L. Gordon, A.Ffield, and R.D. Susanto 2000: Transport and vertical shear variability in Makassar Strait, submitted to J. Phys. Oceanogr., in revised form May 2000.